(Shenyang, China, 1618)

Despite your youth and foreignness, your eventual success in devising a map for Nurhachi has made you a trusted advisor as he prepares for his most audacious venture yet. The eight banners and the seven grievances have been assembled. The question remains where to strike first: Fushun or Yehe? What would the Ming response be to this provocation?

Councillor Eidu favors Fushun; Hurhan favored Yehe. Councillor Fiongon declares that Eidu favors Fushun only because she is an Azure Dragon born a rat. Hohori counters that Fiongon would of course say this, as the Black Tortoise was ascendent at her birth. Hurhan disagrees, pointing out that the Vermillion Bird flew overhead.

Your head is starting to hurt. "Khan." you plead, "You must disregard this advice, based as it is on second-hand astrology. How can the motions of the distant planets have any connection to what occurs here? It is like claiming that we are all marionettes, dancing to the command of the most distant stars!"

This outburst in no way endears you to the powerful astrologer's faction, and they immediately begin to scheme against you, all the more so because they know, in their hearts, that you are right about their craft.

Yet dance we do, to the whims of the stars. If you doubt it, go do a pirouette under the night sky, fill up your bucket, and watch out for the precipice.

When this is, that is. From the arising of this comes the arising of that. When this isn't, that isn't. From the cessation of this comes the cessation of that.

- Buddha, Assutava Sutta

Why is a boat boarded? Why is an arrow fired? Why is a ball dropped?

Why are you reading this book, right now? Presumably you want to — but why? Where did your curiosity come from? And why this, now, rather than some other activity? Careful investigation — including that practiced by both ancient introspective traditions and modern psychology — reveals that even quite internal events and decisions are often the product of chains of causes and conditions that go deeper than we'd like to admit, or generally are aware. Often more obvious are the external factors to which we are ceaselessly subject. Some quite precise course of events caused you to become aware of this book at the exact moment that you did, and no other — can you recall them?

Some causal relations are familiar and everyday: the book is open because your hands pulled the pages apart (or pushed the right buttons). Others are just as clear but take effort to understand: deforestation causes flooding. Some are too complex to fully predict: What changes the weather, or causes currency inflation? Some effects are in proportion to their causes: a refrigerator is shoved; it moves. Others are monumental effects of tiny causes: the timely death of Ogedai Khan in 1242 just prior to the likely invasion and utter demolition of Europe[1], or the *multiple* aversions of nuclear war during the Cuban missile crisis.[2] This causality – "From the arising of this comes the arising of that"– makes up the fabric of our lives and our history; but it is rare for us to fully comprehend its unfolding.

Delving a bit deeper, we see that there is seldom a single cause for a given event, and it is helpful to think in terms of "correlations" and "influences." We can say that there is a *correlation* between *A* and *B* if, given *A*, there is a stronger chance of *B* than would otherwise be expected. This may indicate that *A* causes *B* (or vice versa). Or it could mean that that *A influences B* (or vice versa), if we think of "influences" as partial causes. But a correlation does not necessarily imply direct causation: correlation does not necessarily involve time, and *A* and *B* can be correlated, for example, because they are both influenced by *C*. All of these notions fit into physics, but it also provides a somewhat different framework for understanding causality.

Let's look into this by focusing on gravity. Recall from the experiments with Galileo that gravity here on Earth acts "down" (by definition!), with a force given by the product of the object's mass and the Earth's *gravitational field* at that point. But what determines the gravitational field? Newton, along with his laws of dynamics, supplied a very beautiful answer: every object in the universe creates a gravitational field around itself, proportional to the mass of the object, and inversely proportional to the *square* of the distance away from the object. Adding up the field caused by all objects yields the field at a given point; the gravitation field we feel on and due to Earth is thus built from contributions of every little bit of our planet, which combine to form a field that points down toward Earth's center.

Combining these two ideas, we obtain Newton's famous law of universal gravitation: two objects of mass m_1 and m_2, at distance r apart, each exert upon each other a force F of magnitude

$$F = G\, m_1 m_2 / r^2,$$

where G is a universal constant of nature. This one simple rule describes the forces that hold you to the Earth, the Earth to the Sun, and the Sun to the Galaxy. But while beautiful and successful, Newton's gravity is unsatisfactory.

One aspect that greatly displease Newton was that his gravity appeared to act between distant objects without any sort of contact or intermediary. As he put it in a letter to Richard Bentley: ".... that one body may act upon another at a distance through a vacuum, without the mediation of anything else.... is to me so great an absurdity that I believe no man who has in philosophical matters a competent faculty of thinking can ever fall into it."

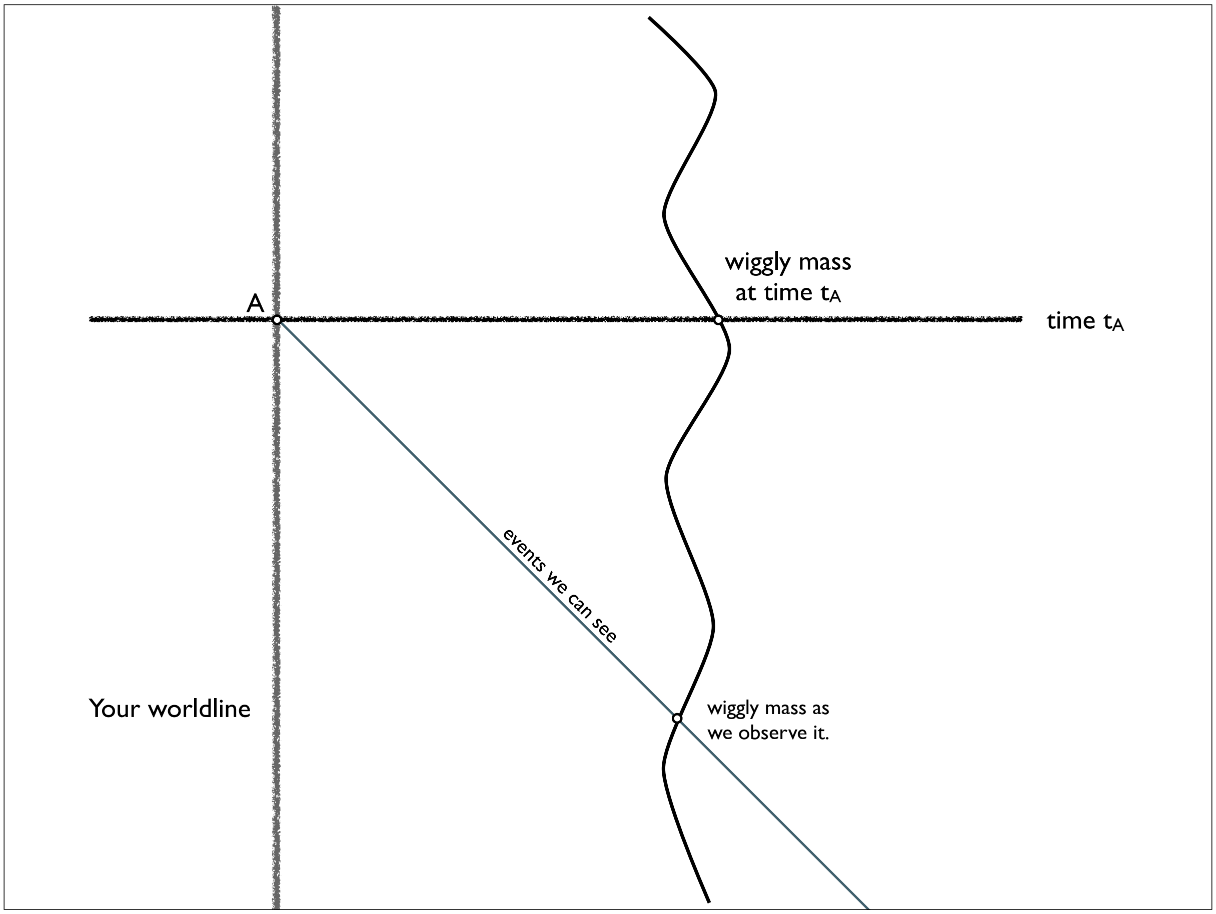
Even worse, though unknown to Newton, is that this action is fundamentally incompatible with Einstein's relativity. To see why, look carefully at how we would use Newton's formula. To calculate the force on one object due to a set of other ones, you must know the distance to all those objects. But the distance can change as the objects all move around. So *at what time* do you calculate the distances? Newton's answer is clear: you assess the positions of all of the objects at the *same time.* But any sort of mention of the "same time," without reference to a given observer, should be immediately troubling: as we've seen, according to Einstein's relativity, different observers will have different definitions of simultaneous. So which time should be used?

In fact the problem is worse. As we shall discuss later, one of the implications of Einstein's relativity is that no object or signal can travel faster than light. Yet according to Newton's formula, someone could wiggle a mass here on Earth and — given sufficiently accurate measurements — this wiggling could be measured at *exactly the same time*, on Mars or anywhere else arbitrarily far away. By wiggling in Morse code, we could communicate with Mars at arbitrarily high speed. Einstein was quick to recognize this flagrant violation of what his theory allowed.

What is to be done? We can take an important step by taking the *gravitational field* much more seriously. We *could* think of this field as just a convenient calculation device encoding everything required to compute the force on an object put at that spot: you just multiply the object's mass by the field. This is completely equivalent to Newton's force law. But we can also take a different perspective, in which the field has a kind of life of its own, as a sort of substance pervading space that can affect gravitating bodies, and in turn is sustained by other gravitating bodies.

The inspiration for this idea comes from understanding the electric and magnetic fields. Just as in gravity, electric charges can exert forces on each other, computable with an inverse-square law just like gravity's. But Maxwell's full equations governing electricity and magnetism do not put it this way! Rather, they describe the electric and magnetic *fields*, which are created by the presence of charges. These fields determine the force that a charged particle feels at a given location. But more interestingly, the fields are not *just* created by particles: electric fields can actually create magnetic fields, and vice-versa. Through this process, the two fields in combination can support propagating disturbances: *electromagnetic waves* — light! Finally, these fields give a clear answer to the issue of how to calculate the electric force. If you move a charged particle, that changes the electric field, but initially only *at the position of the particle*. This change, and hence the changing affect on other particles, then propagates away from the perturbed particle at the speed, it turns out, of light.

We can imagine gravity working in a similar way: the gravitational field is created by particles; if you move the particles, the field responds, and the change *propagates.* Let's assume that as for electromagnetism, the propagation is at the speed of light. Then if you want to know the gravitational field at point A at time t_A, then you must look at all other objects that might provide a field. But you must note their position (and thus distance) at an *earlier* time, which takes into account the delay in the information about their position getting to A. This is shown in the figure below, which shows the worldline for an observer at rest, as well as a wiggly mass some distance away. To know the gravitational field at point A and time t_A, you should not use the distance *d* between A and the wiggly mass at time t_A, but rather the distance between A and the wiggly mass at an earlier time of approximately $t_A - d/c$, i.e. the time at which a photon leaving the wiggly mass would reach point A at time t_A.[3]



To compute a field at position A at time t_A due to material at distance d, you must assess the material at time t_A-d/c, where it crosses the past lightcone of point A.

With this in mind, let's return to the idea of causes and effects in physics. The same considerations that came up with gravity apply to *any* physical process: unless influences propagate at or below light speed, they could be used to send signals faster than light, violating Einstein's relativity. Thus for a given event, only a certain spacetime region could possibly have anything to do with exactly what happens at that event. This region is precisely the "past lightcone" from which signals could travel to the event in question without going faster than light. Events outside of each others' lightcones cannot have a causal relationship with each other. This means not only that they can't send signals between them, but more generally that the information that the laws of physics need in order to determine what happens at one event *cannot include* what happens at the other event. (The events still might be *correlated*, however, by sharing common causes in the past.)

While this captures much of the idea of causality, it is not the whole story, because even influences that can *in principle* affect a given event may be so weak that they are utterly negligible in practice. For example, you are subject to a gravitational force from Mercury, right now. Yet the $1/r^2$ behavior of gravity implies that although Mercury has an enormous mass, its vast distance means that a person standing next to you exerts more gravitational force on you than Mercury does! In fact, none of the planets — even Jupiter — come close to the gravitational influence of a nearby tree or building. And *that* influence, in turn, is absolutely dwarfed by other day-to-day forces: a passing breeze, for example, could easily be a million times stronger. This is why the overwhelming majority of physicists do not believe that astrology can make sense.

So we live quite independent of what the universe faraway is doing, right? Well...perhaps not. Although the force due to a bit of matter decreases with its distance, if the universe roughly uniform, then the amount of matter at a given distance increases with that distance. This is because the "matter at a given distance" is essentially the matter on a sphere with a radius of that distance, and as the distance gets larger, so does the area of that sphere. In fact, this *exactly* compensates for the decrease in force from that distance. That means that in a roughly uniform universe, the influence of matter from each different distance – envisioned as a shell of matter at that distance – would be about the same, regardless of how far away the shell is. And if such a universe were infinite and eternal, the influence on a given point would in fact be dominated by what matter infinitely far away is doing.

In our actual universe, it is more subtle: the effect of the whole observable universe is still small compared even to Mercury's. And yet, at one time our universe was very uniform, and the dominance of nearby scales was much less clear. Is there a residue of this cosmic influence?

In his beautiful book on relativity, Steven Weinberg describes a simple experiment that reveals a deep correspondence:

> First stand still, and let your arms hang loose at your sides. Observe that the stars are more or less unmoving and that your arms hang more or less straight down. Then pirouette. The stars will seem to rotate about the zenith, and at the same time your arms will be drawn upward by centrifugal force. It would surely be a remarkable coincidence if the inertial frame, in which your arms hung freely, just happened to be the reference frame in which typical stars are at rest, unless there were some interactions between the stars and you that determined your inertial frame.

Indeed, what is the origin of the so-called "centrifugal force" that acts on your arms when you spin? An outside observer will object to the idea that there is any force at all: according to them, your arms would prefer to just stay at rest or move in a straight line, in accord with Newton's dynamics. You keep wanting them to rotate with you, so you must apply a force that pulls them into rotation with you. The application of that force is the tugging you feel.

Yet from *your* point of view, it feels just like some mysterious strings are yanking on your arms. Isn't this a valid viewpoint? After all, who is to say what is rotating and what is not? Newton consistently believed in both absolute velocity and acceleration, and argued that we could experimentally determine whether an object — say a rotating water-filled bucket — was in rotation or not with respect to this absolute frame. As he wrote in the *Principia*, "This ascent of the water [up the sides of the bucket] shows its endeavor to recede from the axis of its motion; and the true and absolute circular motion of the water, which is here directly contrary to the relative, discovers itself, and may be measured by this endeavor."

We saw early on that as conformed by countless experiment, there is no meaning to absolute uniform motion. Why, then, should there be some absolute meaning to rotation? Yet if there is only acceleration with respect to something else, when *what is it* that you — or the bucket — are rotating with respect to, when you feel the mysterious outward force?

Ernst Mach, around the turn of the 20th century, gave an answer that was to profoundly influence Einstein's thinking. It is suggested by the first part of Weinberg's experiment: when you feel that you are not rotating, look up at the night sky and note that the centrifugal force is absent when you are not rotating *with respect to the stars*. The implication is that in some way, the cosmic distribution of matter constitutes a non-rotating (and generally non-accelerated) frame. Once this is established, "fictitious" forces, such as the centrifugal one, arise in frames that are accelerated with respect to the cosmic one.

So when you spin around, you're well in your rights to imagine that you are staying fixed and that the universe is spinning around you. As it does so, it exerts a strange influence that pulls your arms away.

Is it a force? Not exactly. (Is gravity a force? Not exactly.)

We're used to cause and effect. What's astonishing is how we make our way through moment after moment affected by causes beyond our knowledge or even understanding.

1. EN: Cecelia Holland in *What If?: The World's Foremost Military Historians Imagine What Might Have Been* by Robert Cowley

2. EN: Perhaps most heroically by the steady nerves of submarine flotilla commander Vasili Arkhapov http://news.nationalgeographic.com/2016/03/you-and-almost-everyone-you-know-owe-your-life-to-this-man/

3. EN: It's pretty clear that given relativity, the "distance at time t_A" depends on the definition of time t_A, (which depends upon the reference frame) and is thus an ambiguous way to compute things.
Using the properties of the wiggly mass at the earlier time "as we observe it" is well-defined however. The light-cone is frame-independent, as it is made up of points connected to A by paths traveling at the speed of light. These have T=0, which is invariant, so all observers agree on which paths are light-like.
But you might object: isn't the distance between the observer and the wiggly mass at this earlier time still frame-dependent? Yes it is! In fact, in Einstein's theory of gravity, which we will look into more in the next case, you don't just use the mass of the wiggly object and it's distance, but also its velocity; these factors all combine perfectly in such a way that the prediction for the gravitational field at point A turns out to be independent of the frame in which you compute it.